NON-INTRUSIVE SCANNING TECHNOLOGY FOR CONSTRUCTION ASSESSMENT

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Abstract: Work at the National Institute of Standards and Technology on laser radar imaging of a construction site is described. The objective of the research is to make measurements required in a construction project quicker and cheaper than current practice and to do so without impacting existing operations. This can be done by developing techniques for real-time assessment and documentation in terms of 3D as-built models of the construction process. Once developed, this technology may be used for other applications such as condition assessment of a hazardous environment where human intervention would be impossible.

Keywords: 3D Models, construction automation, cut-and-fill calculation, laser radar, laser imaging, metrology, terrain modeling.

1. INTRODUCTION

Recent studies by the Construction Industry Institute[1] have indicated that for a typical $100 million construction project between $500,000 and $1 million are spent purely on keeping track of where things are on the site -- typically tens of thousands of items -- and monitoring the status of construction activity. Further expenses are directed to the establishment of the state of the infrastructure following the actual construction work. Thus, approximately 2 % of all construction work must be devoted to manually intensive quality control and tracking of work package completion, including operations involving earthmoving and bulk materials handling. Any technology that can reduce this burden and decrease time to delivery will offer a significant competitive edge. It should be further emphasized that any technology that delivers automated, rapidly available information relating to project status and the position of components at the site would also leverage further cost savings by supplying that information to automated and semi-automated systems performing work at the site.

One of the more difficult things to track at a construction site is the geometry of things which are not neatly classified as "components." The ability to capture such "amorphous" data becomes important if one is to achieve true automation. Amorphous data include such things as the state of excavation of terrain, the presence of raw materials (e.g. sand, gravel) depots; the location and extent of spoil piles; progress of a concrete casting; highway alignment; paving operations; etc. To obtain this information, the current state-of-practice is to conduct surveys. These surveys involve: 1) Field work and data acquisition - making measurements and recording data in the field 2) Computation and data processing - calculations based on recorded data to determine locations, areas, volumes, etc. 3) Mapping or data representation - plotting of measurements to produce a map, chart, or plat, and, for earth moving, the placement of grade stakes on the site -- a practice that even small construction companies recognize as inefficient.

Equally important is the need to automatically capture the "as-built" condition of an existing structure, or to capture and clarify a complex construction operation as it happens and to provide real-time feedback to those conducting the operations. All of these are complex situations where traditional metrology techniques are not effective, due to the massive quantities of data

[1] An industry consortium comprising some 100 of the USA's largest contractors, AE design firms, and building owners. See, e.g., "1997 Strategic Plan & Governance Plan," **Construction Industry Institute**, Austin, TX, February 1997 and the in-progress report of Committee 151, on RFID Technologies.

needed to describe the environment. The research discussed herein focuses on the use of new fast laser ranging technologies and three-dimensional analysis to automatically and non-intrusively scan a construction site and to mine useful information from that data for project planning and documentation purposes.

The National Institute of Standards and Technology's (NIST) project in *Non-Intrusive Scanning Technologies for Construction Status Assessment* builds on metrology, wireless communications, and simulation research conducted as part of the National Automated Manufacturing Testbed (NAMT) collaboration [4]. The objectives of the project are to utilize new scanning technologies to improve critical construction status assessment needs by making these measurements faster and cheaper than traditional methods and to develop, in conjunction with industry, standard means for transmission and interpretation of such data.

1.1 Scope of Project

The research project was initiated in October, 1998. It focuses on the development of an integrated software and wireless remote sensing system that will accept input from a variety of high speed automated ranging sensors and create a 3D model of the present state of a portion of a construction site. As an initial, full-scale practical demonstration, site topography during the construction of the Building 205 Emission Control System at NIST is being tracked. Emphasis is on the use of non-intrusive scanning systems that can acquire site geometry, yet do not require instrumentation to be installed on earthmoving machinery. This is important for initial introduction of the technology to the construction industry as most contractors are reluctant to test new technologies and methods if it means an increase in their costs. The models generated in this fashion (from the actual Building 205 construction site) will be compared against those acquired by means of an all-terrain vehicle (owned and operated by NIST) equipped with a real-time-kinematic (RTK, cm-level) global positioning and attitude determination system. Derivative quantities such as remaining cut-and-fill volumes, overall progress rate, and projected completion date will be displayed by means of a graphical user interface at the construction site office; ultimately, the same information will be able to be delivered directly to the operator of the appropriate earth moving machinery.

The work focuses on (1) scene update rate requirements and methods for improving scene update rates; (2) development of standardized means for transmitting and interpreting scan-data packets; and (3) development of practical post-processing routines that automatically operate on the 3D data to produce useful derivative quantities identified in collaboration with the construction industry. This is a base-technology development project combined with practical, full-scale demonstrations to industry. Its various elements will be subsequently used as building blocks to address more complex 3D as-built assessment problems for construction industry.

Collaborations are being established with construction industry partners to ensure that (1) the technology developed is responsive to industry needs, and (2) the technology developed is usable in a construction context.

The excavation tracking technology developed during this project will be tested first at the Building 205 construction project on the NIST, Gaithersburg campus, scheduled to begin in late 1999. The procedures developed during this project will be extended to the much larger Advanced Measurement Laboratory construction project ($300 million, U.S.) during the 2000-2002 time frame. Long-term research is being directed to the use of high speed, precision laser radars (LADARs) as an automated means of as-built discrete component identification and placement assessment.

To achieve these objectives, several tasks were identified:

1. Develop a laser ranging system that can image a construction area in "real-time".
2. Develop the ability to wirelessly transfer range data from the field to a remote office.
3. Link the rangefinder to GPS position and attitude measurement systems so that the range data can be registered to a known reference frame.
4. Develop a user interface:
    a. To automatically operate the scanner.
    b. To display the 3D data.
    c. To determine cut/fill requirements.

2. LASER SCANNER

There are two principle categories of scene imagers presently under consideration at research labs and commercial industry. The first bases its operation on measuring the time-of-flight of a coherent light pulse. The use of a pulsed diode laser will enable, presently, a range measurement to be made over several scores of meters in daylight to "non-cooperative" targets (i.e. natural targets without the use of retroreflectors) with an update rate of around 25 kHz maximum. In order to develop a scene image, this type of unit must be swept in raster mode. The unit output is typically in the form of scan lines, with each scan line progressively stepping across the scene within the field of view of the instrument. A variant on the time-of-flight design is the "flash" ladar [3] in which a relative high energy, diffuse pulse "illuminates" the scene. The returned photons are then optically guided to a photomultiplier array which permits individual time- of-flight range measurements to be made simultaneously over a matrix representing the scene. In principle this approach offers the most direct path to "real-time" performance, yet it remains a research tool. An alternative approach involves the use of a continuous wave (cw) laser interferometer that determines range based on phase difference. This type of unit is typically operated in a raster scan mode, similar to the pulsed diode ladar. An obvious drawback to all of these rangefinders is that they cannot “see” through objects and thus scans from different locations need to be acquired and registered to obtain a composite, unobstructed view.

The majority of the rangefinders used in surveying employ lasers with wavelengths in the infrared region and are eyesafe. The maximum range of these range finders varies from less than 12 m to greater than 50 km with the penalty of reduced accuracy at the longer distances.

The accuracy of the measurement is influenced by many factors with the main ones being the reflectivity of the object and the existing environmental conditions. Bright sunlight, rain, snow, fog, smoke, and dust will adversely affect the accuracy of the measurement. Accuracy may be increased by increasing the measuring time, the signal power, and by taking multiple readings.

2.1 Description

There are a few commercially available ladars. The criteria used in selecting a rangefinder for this project were 1) speed in acquiring the range data 2) accuracy 3) maximum range, 4) commercially available 5) cost and 6) resolution. The requirement for real-time update requires that the frame rate be at least 10 Hz.

For purposes of obtaining an as-built model, positioning, alignment, etc., the required accuracy had to be on the order of millimeters. The maximum range required to scan a construction site is about 100 m to 200 m.

There is no laser rangefinder currently available that comes close to meeting the first requirement. This, however, is not a detriment to the present NIST research for two reasons. First, the project focus is on exploring the utility of non-intrusive scanning techniques and the use of a slower model does not yet adversely affect the development of basic post-processing tools. Secondly, due to efforts both within and outside NIST, the technology will “catch up” very quickly.

Based on the above discussion, a custom scanner was developed for the NIST research reported herein by Riegl[2]. The laser profile measuring system consists of a high precision pan/ tilt mount, laser rangefinder, and laptop control computer. This system will henceforth be referred to as "the laser scanner."

The laser scanner is a Class 1 (eyesafe) system that emits an infrared laser pulse with a wavelength of 905 nm ± 5 nm. It can be set for automatic or manual scanning. The scanning field-of-view (FOV) is ±180° horizontally and ±150° vertically which permits an exceptionally large area to be imaged. The scan rate is 36°/s both in the horizontal and in the vertical directions. The range of the laser scanner is up to 150 m for objects with reflection coefficients, ρ, greater than 80 % and 50 m for objects with ρ of greater than 10 %. Distance measurements have a typical accuracy of ±20 mm and ±50 mm in the worst case (due to dust and atmospheric effects). Beam divergence is approximately 3 mrad.

A windows based interface program allows the user to set parameters to operate the laser scanner. Basic input requirements are: start horizontal angle, start vertical angle, incremental angle in both horizontal and vertical directions, number of data points in a scan line, and the number of scan lines.

2.2 Typical Scan Characteristics

A sample scan of the NIST TTF laboratory was obtained and is displayed in the form of a point

[2] Certain trade names or company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

cloud in Fig. 1. The 2-1/2 D image consists of approximately 40 000 data points - 200 points per scan line and 200 scan lines. The actual number of data points is somewhat less than 40 000 because in some cases no signal was returned – typically, diffuse black objects make poor targets. The horizontal and vertical angles were set to 90° and angle increments were set to 0.45°. The scan acquisition time was approximately 7 min. The range data contained in this very coarse image are still sufficient for the naked eye to easily pick out many components including ladders, access doors, scaffolding, test fixtures, and an overhead crane. Dense data of this class, registered with similar data taken from other points of view, will provide the raw information upon which component identification algorithms operate.

3. AUTOMATIC CUT AND FILL SURFACES

Current work at NIST involves automatically creating a 3D surface image of the scanned excavation area as shown in Fig. 2. This is accomplished by mounting the ladar unit on a heavily instrumented all-terrain vehicle (ATV) which automatically registers the ladar data to the job site using precision GPS position and attitude reporting and a geometry transformation to adjust for non-collocated instrumentation. The composite data is wirelessly uplinked to a dynamic site database, wherein the terrain data become available for subsequent derivative quantity calculations. Given a second, arbitrary NURBS (Non-uniform rational B-spline) surface specifying the desired excavation profile (the architectural intent), the objective is to determine the cut/fill requirements. The creation of the 3D image as a surface necessitates the meshing of a point cloud with polygons. That is accomplished by implementing a Delaunay technique [2] to create a mesh for a regularly or irregularly gridded point cloud. This implementation is capable of performing adaptive sampling to reduce the number of points in a region of dense data points and the method of least squares is used for smoothing the meshed surface.

Using the actual terrain shown in Fig. 2 as a sample excavation site model and assuming, for the purpose of simplified example here, the desired excavation profile is a horizontal surface at an elevation of $z = 2$ m, the cut/fill requirements can be calculated by summing the volumes of the triangular prisms between the two meshed surfaces. The volumes are computed by multiplying the projected area of the triangle by the average of the height of the prism and then summing up the volumes for all the prisms. Fig. 3 shows the cut-and-fill surface while Fig. 4 shows the Data Explorer [1] visual script used to generate the image.

The use of an existing in-house (NIST developed) software package and commercially available software packages such as Data Explorer, IDL, and products from Intergraph, and AutoDesk to compute and display the cut/fill requirements are being investigated in parallel. From these studies, we anticipate the development of automated information transfer protocols for the uplink of both construction site terrain data as well as discrete component locations.

4. FUTURE WORK

Future work in the upcoming year includes registering data from different scan locations, using RTK global positioning devices to establish a common reference frame for the data points, and using the scanning technology to track the progress and document the construction of the emissions control facility for Building 205 at NIST.

In the longer term, object recognition (human-assisted in the beginning with the end goal of full automation) will also be investigated. This will allow dense scanned data to be replaced by more compact 3-D model (e.g. VRML) representations and will advance the goal of obtaining automated 3-D as-built models. NIST is also pursuing the development of more advanced imaging devices through its Advanced Scanner Initiative.

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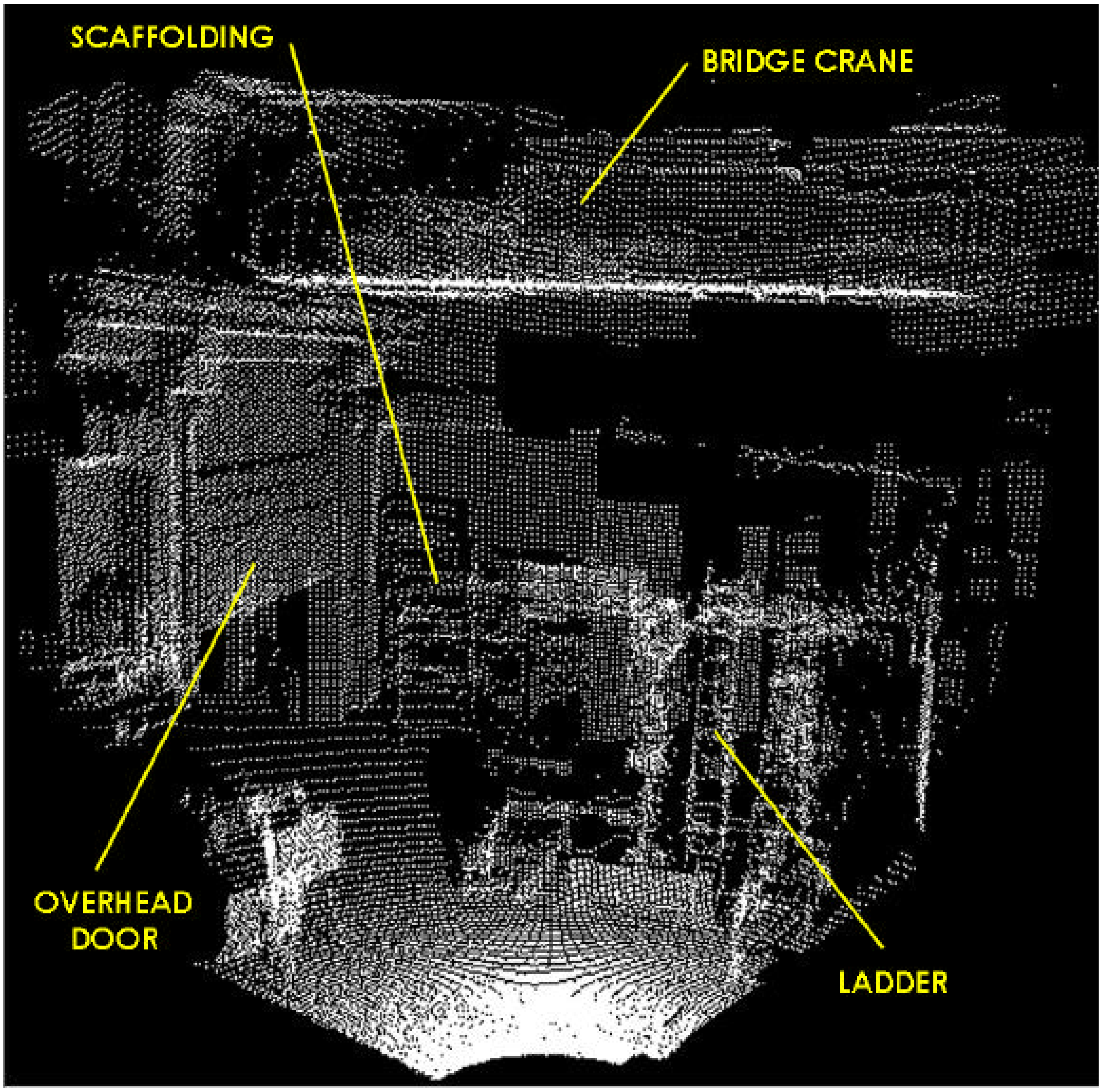

Figure 1. Actual ladar scan of a familiar NIST site: the Building 226, Structures Lab Tri-Directional Test Facility (TTF). This image provides an example of the dense clutter to be expected at an everyday construction site.

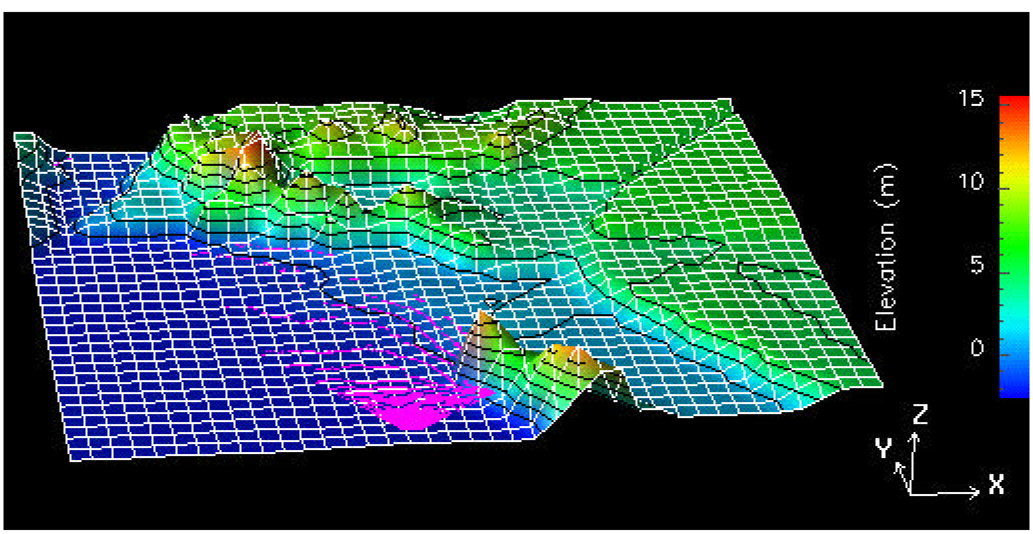

Fig. 2. Meshed surface of scanned terrain on NIST campus created using Data Explorer scripts.

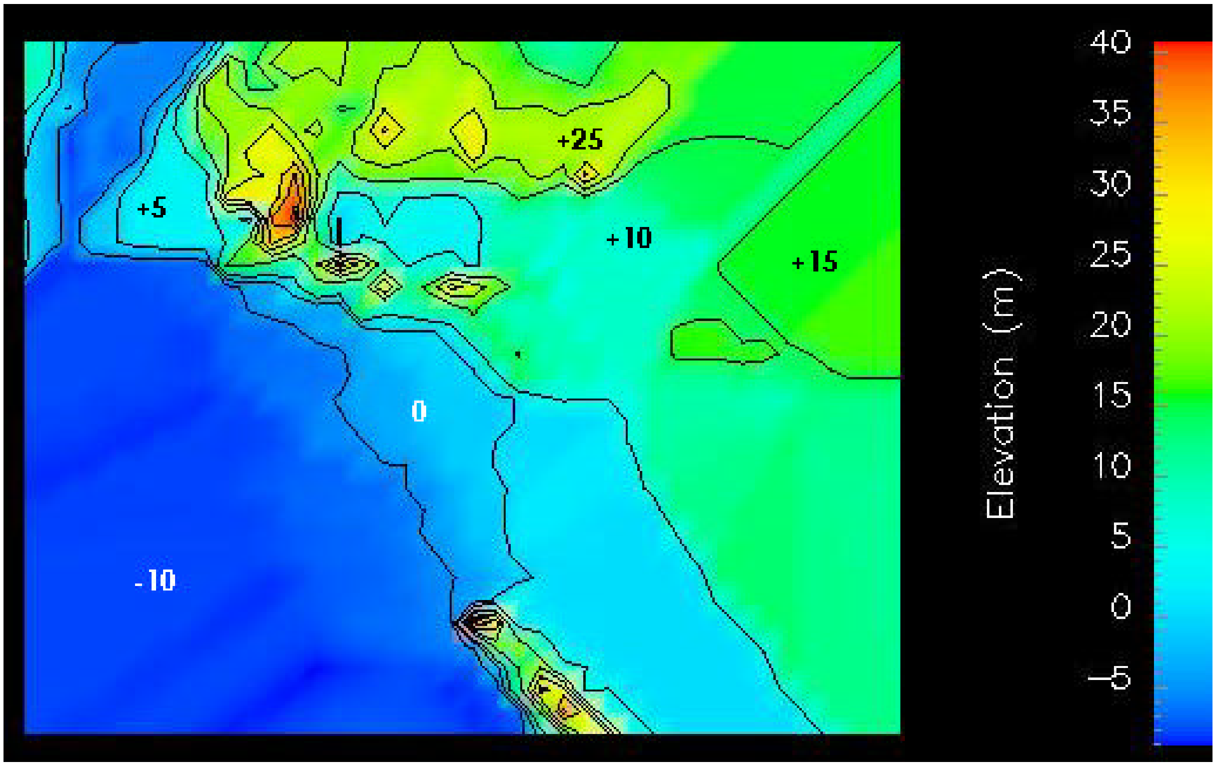

Figure 3. Automatically generated cut/fill map created by operating on the 3D terrain model of Fig. 2 with a final target elevation at z = 2 m. Negative numbers represent fill requirements (in m) while positive contours represent cut requirements.

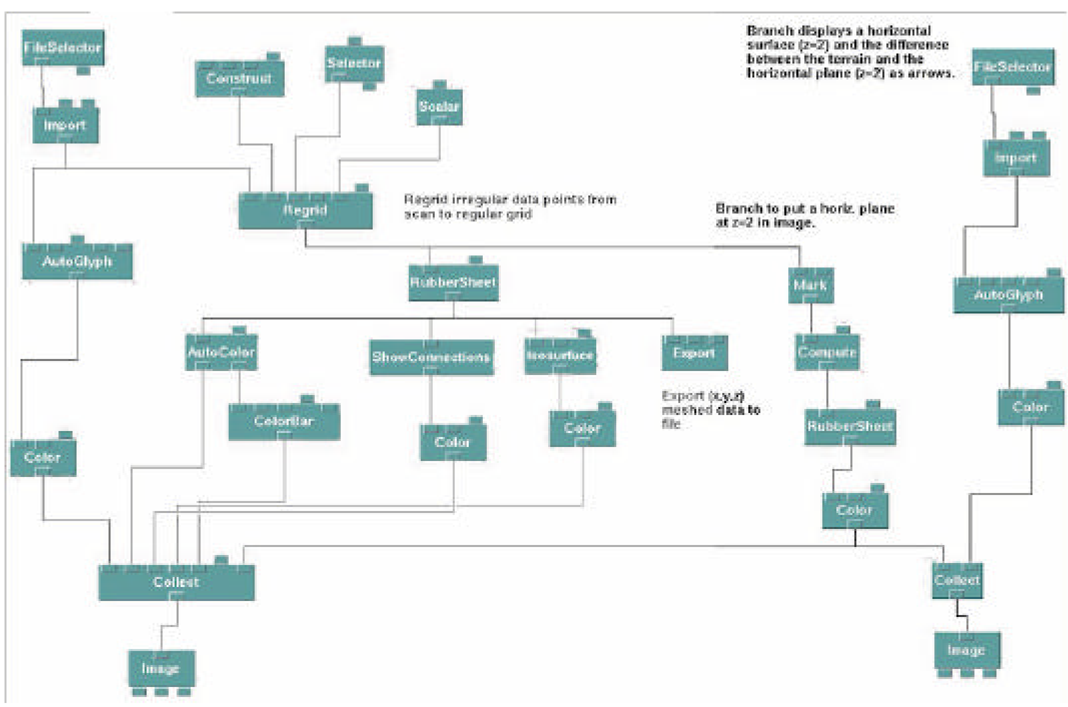

Figure 4. The scanned data are imported using the import module. A file is then opened containing x, y, and z data values and stored as a 2-vector (x, y position) location and a scalar value (z). Modules *construct*, *regrid* and *rubbersheet* are the primary modules. Construct defines the mesh size and origin. Regrid maps the scattered points onto a grid. The module allows for the specification of the number of nearest points to the grid point to be used to calculate the average data value

for that grid point. A radius may also be defined within which the nearest neighbors can be found. The module rubbersheet deforms the surface based on the data values (z-values) of the surface.